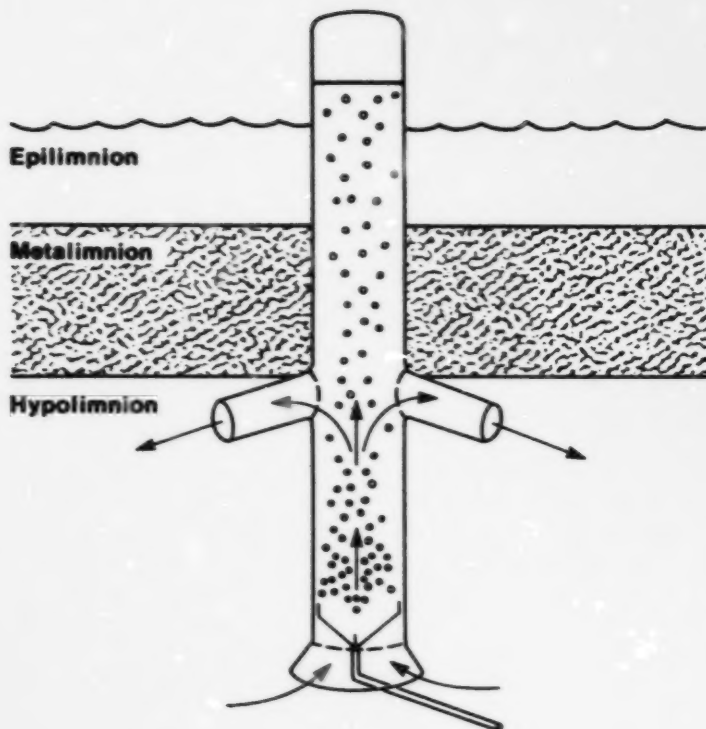


A Review of Lake Aeration as a Technique for Water Quality Improvement

APD Bulletin 22



C
5AB

6:22
982
2

LEGISLATIVE COUNCIL
VICTORIA, B.C.



Province of British Columbia Ministry of Environment

84- 4340 /



Province of British Columbia
Ministry of Environment
ASSESSMENT AND PLANNING DIVISION

APD Bulletin 22

A REVIEW OF LAKE AERATION AS A TECHNIQUE FOR WATER QUALITY IMPROVEMENT

by

R.N. Nordin

C.J.P. McKean

AQUATIC STUDIES BRANCH

Victoria, B.C.

February, 1982

Canadian Cataloguing in Publication Data

Nordin, Richard Nels, 1947-

A review of lake aeration as a technique for
water quality improvement

(APD bulletin, ISSN 0228-5304 ; 22)

Bibliography: p.

ISBN 0-7719-8888-5

1. Lakes - Aeration. 2. Lakes - Aeration - Bibliography. I. McKean, Colin J. P. (Colin John Pearce), 1955-. II. British Columbia. Ministry of Environment. Assessment and Planning Division. III. Title. IV. Series.

Z7935.N67

016.6281'65

C82-092091-6

© Copyright 1982. B.C. Ministry of Environment
First Printing 1982.

SUMMARY

Aeration of lakes and reservoirs has been used for a number of years as a method of improving water quality. Aeration can be used for improvement of drinking water supplies, providing enhanced fisheries habitat and treatment of symptoms of eutrophication.

Aeration can be arbitrarily divided into two basic categories. Destratification systems, as the name implies, uses compressed air to cause vertical water movement and mixing of the lake water column. Hypolimnetic systems add oxygen to the lake without destroying the thermal stratification. Each type are appropriate in particular situations.

The largest portion of the report is a bibliography listing journal articles and reports documenting experiences with aeration projects.

TABLE OF CONTENTS

	Page
SUMMARY	i
TABLE OF CONTENTS	ii
LIST OF TABLES	iii
LIST OF FIGURES	iii
ACKNOWLEDGEMENTS	iv
1. INTRODUCTION	1
2. AERATION SYSTEM TYPES	2
2.1 Historical Development	2
2.2 Destratification Systems	2
2.3 Hypolimnetic Systems	8
3. CONCLUSIONS	13
4. REFERENCES	14

LIST OF TABLES

	Page
1. Summary of Information for Selected Destratification Projects	7
2. Summary of Information for Selected Hypolimnetic Projects	10

LIST OF FIGURES

1. Destratification System	3
2. Hypolimnetic Aeration Units	11
3. Hypolimnetic Aeration Units	12

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Roland Rocchini and Dr. Ron Buchanan of the Aquatic Studies Branch and Ken Ashley of the Fish and Wildlife Branch, Fisheries Research Section, who reviewed the manuscript and suggested several improvements which were incorporated into the final version.

1. INTRODUCTION

A literature review on lake and reservoir aeration was originally done at the request of the Okanagan Implementation Program as part of an evaluation of the feasibility of aerating Wood Lake. This report is a compilation of that work considered in a general format so that the information could be available to those individuals and agencies for whom the information would be useful. It is not intended to be a "do-it-yourself" manual, but rather a general overview of present information and a guide to the literature on aeration.

2. AERATION SYSTEM TYPES

2.1 Historical Development

Lake aeration was first described by Scott and Foley (1919). However, little activity with regard to lake aeration is evident in the literature until a paper by Mercier and Perret (1949), brought the concept forth again. During the 1960's and 1970's numerous projects were undertaken, and the sophistication and size of many of the projects increased dramatically after that time. All of the early systems used were the destratification type where air is pumped from a shore station into the lake, through a perforated line anchored near the bottom of the lake (Figure 1). The air escaping from the hose rises through the water column, inducing vertical mixing and preventing the normal thermal stratification of the lake. The action of the rising bubbles apparently transfers very little oxygen to the water (King, 1970). Rather, the circulation pattern which is established allows gas exchange at the lake water surface and mixes this aerated water back to the bottom of the lake (Smith et al., 1975). This type of system and variations of it are considered below, while the other general category of aeration (hypolimnetic) is considered in the following section.

The thermal stratification of a lake can be destroyed without aeration. Mechanical mixing has been used successfully (Ridley 1972; Gebhart and Clady, 1977; Irwin et al., 1966) and this method is also an option for destratification.

2.2 Destratification Systems

Destratification was first used by fisheries managers to solve the problems of deoxygenation of the hypolimnion of productive lakes. Lack of oxygen in the hypolimnion during the summer restricts the habitat of fish to the epilimnion. The high surface water temperature affects the growth rates and survival of species (like trout) that prefer cool water. In winter, many productive lakes tend to 'winter kill', that is they have insufficient oxygen

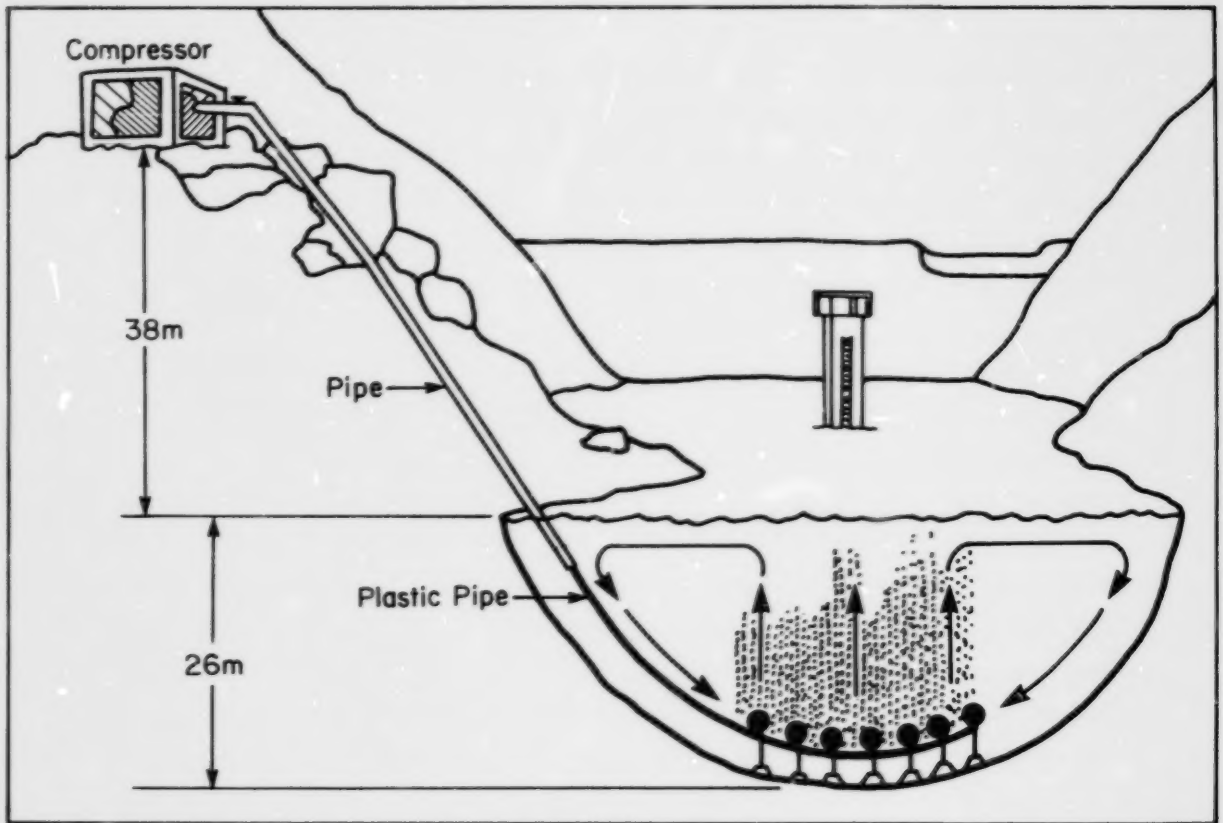


FIGURE 1: Destratification system (from Lorenzen, 1977a).

content to allow survival of fish through the entire period of ice cover. In both of these situations aeration can be a useful method of habitat improvement. Some of the early aeration projects undertaken for fisheries enhancement were in British Columbia (Halsey, 1968; and Halsey and Galbraith, 1971) as well as a variety of other locations: California (Fast, 1968); Colorado (Lackey, 1971; Lackey and Holmes, 1972); North Dakota (Tubb, 1966; Kreil, 1969 and 1971); Wyoming (Rasmussen, 1960); and Wisconsin (Wirth, 1970; Wirth and Dunst, 1967; Wirth et al., 1970). The B.C. Ministry of Environment, Fish and Wildlife Branch continues to be very active in research and application of hypolimnetic aeration systems (Ashley, 1981; and Ashley, in prep.).

Destratification by aeration provides a relatively inexpensive means of mixing the lake and destroying (or minimizing) the stratification. It can be used to accomplish a number of ends.

The use in fisheries management has been noted above. Destratification basically increases the oxygen content of an entire lake. During the summer destratification has one major disadvantage. Constant circulation of the lake may allow the heat content to increase to a point where the advantages of the increased oxygen content are overshadowed by the temperature constraints on a cold water fishery. The hypolimnetic aeration systems described below solved the problem of increased heat budget by aerating without disturbing the temperature stratification.

Destratification aeration can also be used in improvement of drinking water quality by both aerating the water column when problems of low oxygen concentrations are encountered, and controlling high algal growth. This latter aspect is one which requires a detailed evaluation of the conditions prevailing and some projections as to the effects of aeration. Destratification may reduce algal growth in three ways. First, by simply causing mixing of the algal biomass present into the entire water column, the algae are not restricted to the photic zone (Fast, 1968; Bernhardt, 1967). This does not reduce the amount of algae in the lake, it merely reduces the concentration. Second, by having the algal cells travelling vertically through the water

column, part of the time they are below the photic zone and the growth rate is slowed (Lorenzen, 1977a and 1977b). A third mechanism of reduction of algal growth is by reduction of nutrients by altering the chemical nature of the water column and conditions at the sediment-water interface. Under anaerobic conditions, phosphorus particularly is mobilized from lake sediments and a flux from the sediments to the water column takes place. When the sediment is overlain with aerobic water, the phosphorus tends to be bound to iron, aluminum or manganese and remains in the sediment.

It has also been reported that aeration can cause changes in the composition of phytoplankton in a lake or reservoir, from blue-green algae which are particularly undesirable in terms of aesthetics, taste and odour and toxicity, to less objectionable green algae (Shapiro et al., 1977; and Malueg et al., 1971). Taste and odour problems can also be overcome to some extent by aeration (Shuler, 1972) through oxidation of reduced organic and inorganic compounds.

However, destratification can act to maintain or even increase algal growth under some circumstances. Destratification aeration tends to slow the normal sedimentation processes by which algal cells sink from the surface waters to the sediment and are lost, more or less permanently, from the lake. Also, if a destratification system is started up after lake stratification has been established, the consequences can be overwhelmingly negative. Circulation of high concentrations of nutrients into the surface waters have, in a number of cases, caused algal blooms (Brown et al., 1971; Knoppert et al., 1970). If the hypolimnetic water has a high oxygen demand because of dissolved or suspended oxygen consuming materials (hydrogen sulphide or ammonia), a kill of fish and perhaps other components of the biota (zooplankton, benthos) could result from the rapid loss of oxygen from the lake. Lastly, if a lake is shallow, destratification may not reduce algal growth (Bryan, 1964; Malueg et al., 1971; and Knoppert et al., 1970). Brown et al., (1971) noted algal growth in Buchanan Lake (Ontario) increased following destratification. In all these cases the lake's maximum depth was less than 13 m. Consequently, the success of destratification in reducing algal growth may be restricted by the depth of the lake. Lorenzen and Mitchell (1973, and

1975), and Lorenzen (1977a, and 1977b) outline the conditions where destratification can be used to control algal growth.

It is prudent to start operation of a destratification system in the spring or fall while the water column is isothermal. The system can be installed at any time of the year although it may be advantageous to use warm summer weather to uncoil and install diffuser tubing. Start-up during isothermal conditions allows the aeration system to maintain aerobic conditions, and prevent the build-up of ammonia and hydrogen sulphide in the hypolimnion and disruption of the oxidized film on the sediment surface which prevents release of phosphorus from the sediments into the water column. For prevention of winterkill this also is the best strategy (Lackey and Holmes, 1972). Beginning operation of a destratification system before spring and winter stratification is the most efficient use of energy since little power is required to circulate an isothermal water column and keep it circulating. However, to destratify an existing, well established thermal stratification requires a larger input of energy and is more difficult to accomplish.

There are also a variety of other precautions required in system design. For instance, the perforated air supply line must be elevated above the bottom to preclude suspension of fine sediments into the water column (Barica, 1974; Haynes, 1973 and 1975).

Excellent reviews of the parameters which are required prior to consideration of a destratification system are contained in Lorenzen (1977a and 1977b), Fast (1979), Lorenzen and Fast (1977), Toetz et al., (1972) and Lorenzen and Mitchell (1975). Information and results of selected destratification projects are summarized in Table 1.

There are a variety of other uses for destratification systems: aeration of waste water lagoons, prevention of ice formation around structures in lakes and reservoirs, and containing oil spills. These uses have extensive literature which can be referred to, but have not been considered in this report.

TABLE 1

SUMMARY OF SOME INFORMATION FOR SELECTED DESTRATIFICATION PROJECTS

Destratification Systems

Lake	Location	Reference	Diffuser Depth (m)	Air Flow (CF/M)	Pump Power (HP)	Surface Area (ha)	Lake Volume (dam ³)	Max Depth (m)	Mean Depth (m)	$\frac{Qa^*}{V^{**}}$	$\frac{Qa}{A^{***}}$	Comments or Observations
Blenheim Tarn	U.K.	Bryan, 1964				10.9		13.4				Decreased iron, phosphorus, and manganese; algae crop was not reduced by mixing.
Buchanan Lake	Ontario Canada	Brown et al., 1971	13	10	2	8.9	435	13	4.9	0.67	10.8	Total Phosphorus decreased greatly although algal crop increased 500-600%. Water clarity decreased by 50%. Zooplankton increased 4 x.
Castas Reservoir	California U.S.A.	Fast, 1968	42.7	630	150	1063	294,792	64	27.7			Reduction in algal blooms. Oxidation of manganese (implies oxidation of phosphorus). pH lowered 0.5 relative units.
Clines Pond	Oregon U.S.A.	Malueg et al., 1971	4.6	1	1/4	0.14	2.7	4.9	1.95	10	65.3	Aeration reduced phosphorus, and produced a shift away from blue green algae. No concentration change in chlorophyll.
El Capitan	California U.S.A.	Lorenzen, 1977	28.4	215	50 elec.	186	17,984	62	9.5	0.30	9.0	Total phosphorus reduced after aeration.
Kezar Lake	New Hamp. U.S.A.	Haynes, 1973, and 1975	7.6	105		71	2,159	8.2	3.04	1.3	13.8	Phosphorus was not reduced as suspended P and was stirred up. Blue green algae were reduced. Green algae became dominant.
Mahnbach Reservoir	West Germany	Bernhardt, 1967	42.7	210	68	215	41,625	43	19.2	0.14	9.1	Oscillatoria rubescens was hindered and manganese and phosphorus were reduced (oxidized)
Cox Hollow	Wisconsin U.S.A.	Brezonik et al., 1969	8.8	72	7.5	39	1,480		3.8	1.4	17.2	Marked decrease in manganese concentrations.
Lake Maarsveen	Netherlands	Knoopt et al., 1970	19.2	88		60.7	8,017	30	14	0.31	13.5	Single diffuser not as effective as distribution network. Also smaller air holes will give best results when used at a minimum overpressure.
Zeeuws-Vlaanderen Reservoir #2	Netherlands	Knoopt et al., 1970	9.5	71		25.5	2,405	10.7	9.5	0.84	26.3	Algal growth was promoted by aeration when the reservoir level fell below 6.6 m. Algal blooms are better controlled in deep reservoirs.

* Qa = Air flow in cubic feet/minute.** V = Volume of lake expressed as $V \times 10^6$ cubic feet.*** A = Area of lake expressed as $A \times 10^6$ square feet.

2.3 Hypolimnetic Systems

Hypolimnetic aeration is a more recent development than destratification systems. The first major projects were carried out in the late 1940's on Lake Bret, Switzerland (Mercier and Perret, 1949), and in the mid 1960's on Wahnbach Reservoir in Germany (Bernhardt, 1967). With destratification systems the design is more or less simple. However with hypolimnetic systems, a large number of variations in the design of systems exist (Figures 2 and 3). Most use compressed air, although pure oxygen has been used (Fast et al., 1975; and Speece, 1973a and 1973b) (Figure 3(b)).

Hypolimnetic aeration was developed in an attempt to solve some of the problems inherent in destratification systems, particularly to maintain the cold water layer at the bottom of a lake or reservoir. The technique introduces oxygen to the water at the bottom of the lake without disrupting the thermocline. This is important for consideration of fisheries habitat and drinking water supplies, and where maintenance of a warm epilimnion is important (e.g., for swimming) or where mixing of nutrients from the hypolimnion into the epilimnion is important (e.g., for algal bloom control). There are a few disadvantages when compared with destratification systems. The supply of oxygen to the hypolimnion is relatively slow because of the small surface area available in the aeration apparatus across which the oxygen transfer is made. Hypolimnetic currents or any induced circulation from the aeration apparatus can be significant because of the relative thermal homogeneity and low resistance to water movement. The limiting factor appears to be the supply of oxygen. For water bodies with large hypolimnia or large surface areas, several units must be considered.

With hypolimnetic aeration with compressed air, nitrogen supersaturation can occur. Fast (1975) notes nitrogen supersaturation is of concern for reservoirs capable of releasing water containing above normal nitrogen gas concentrations on a downstream fishery. Because of these design limitations, most hypolimnetic aerators tend to be more complex and hence more expensive than destratification aerators.

Hypolimnetic aerators can be further distinguished into two basic groups: full lift and partial lift, and the two have different potentials in terms of nitrogen supersaturation. Full lift systems transfer water from the hypolimnion to the surface and consequently back to the hypolimnion (Figures 2(d), 3(a)). These systems tend to be less prone to causing nitrogen supersaturation in the hypolimnion than the submerged, partial lift systems (Figures 2(a)(b)(c)). This can be an important aspect when fisheries may be affected. Supersaturation to 140-150% have been reported (Fast et al., 1975, Fast 1979).

Hypolimnetic aeration can be used for many of the same purposes as destratification aerators. These include correction of summerkill or winterkill conditions for fisheries, reduction of concentrations of hydrogen sulphide and other reduced compounds which can impart unacceptable taste and odours to drinking water supplies, and improvement of the overall water quality of lakes by reducing the supply of nutrients which are released from the sediments particularly during periods of low oxygen concentration (Bengtsson and Gelin, 1975). The supply of nutrients from sediments ("internal loading") can form a significant portion of the phosphorus supply to the lake under certain conditions. In these situations, aeration can be an effective method to reduce the nutrient concentrations of the lake and improve the overall water quality. A fairly detailed nutrient budget is required before aeration is considered as a possible treatment in order to insure that the sediments are a significant source of nutrients.

Table 2 summarizes information and the results of some hypolimnetic aeration projects.

TABLE 2

SUMMARY OF SOME INFORMATION FOR SELECTED HYPOLIMNETIC PROJECTS

Hypolimnetic Systems

Lake	Location	Reference	Diffuser Depth (m)	Air Flow (CF/M)	Pump Power (HP)	Surface Area (ha)	Lake Volume (dam ³)	Max Depth (m)	Mean Depth (m)	$\frac{Qa^*}{V^{**}A^{***}}$	Comments or Observations
Lake Grebner	West Germany	Dunst et al., 1975				50		25			Total phosphorus and primary production decreased. There was an increase in clarity and hypolimnetic oxygen.
Hemlock Lake	Michigan U.S.A.	Fast, 1971a & 1975				1.8		18.6			Reduction in pH. Problems with aeration tower. Nutrients leaked to epilimnion. Phytoplankton increased.
Lake Jarlasjon	Sweden	Bengtsson and Gellin, 1975				84		24			Oxidation of sediments eliminated internal phosphorus recycling.
Mirror Lake	Wisconsin U.S.A.	Smith et al., 1974		17		4.5		13			Aeration did not raise hypolimnetic O ₂ above 0.5 mg/L but phosphorus levels declined. Phosphorus levels in hypolimnion rose again after aeration stopped.
Wahnbach Reservoir	West Germany	Bernhardt, 1967	18	142	50	215	41,625	43	19.2		Cool oxygenated water was available for drinking. Phosphorus was not released from the sediments during aerobic periods.

* Qa = Air flow in cubic feet/minute.

** V = Volume of lake expressed as V x 10⁶ cubic feet.*** A = Area of lake expressed as A x 10⁶ square feet.

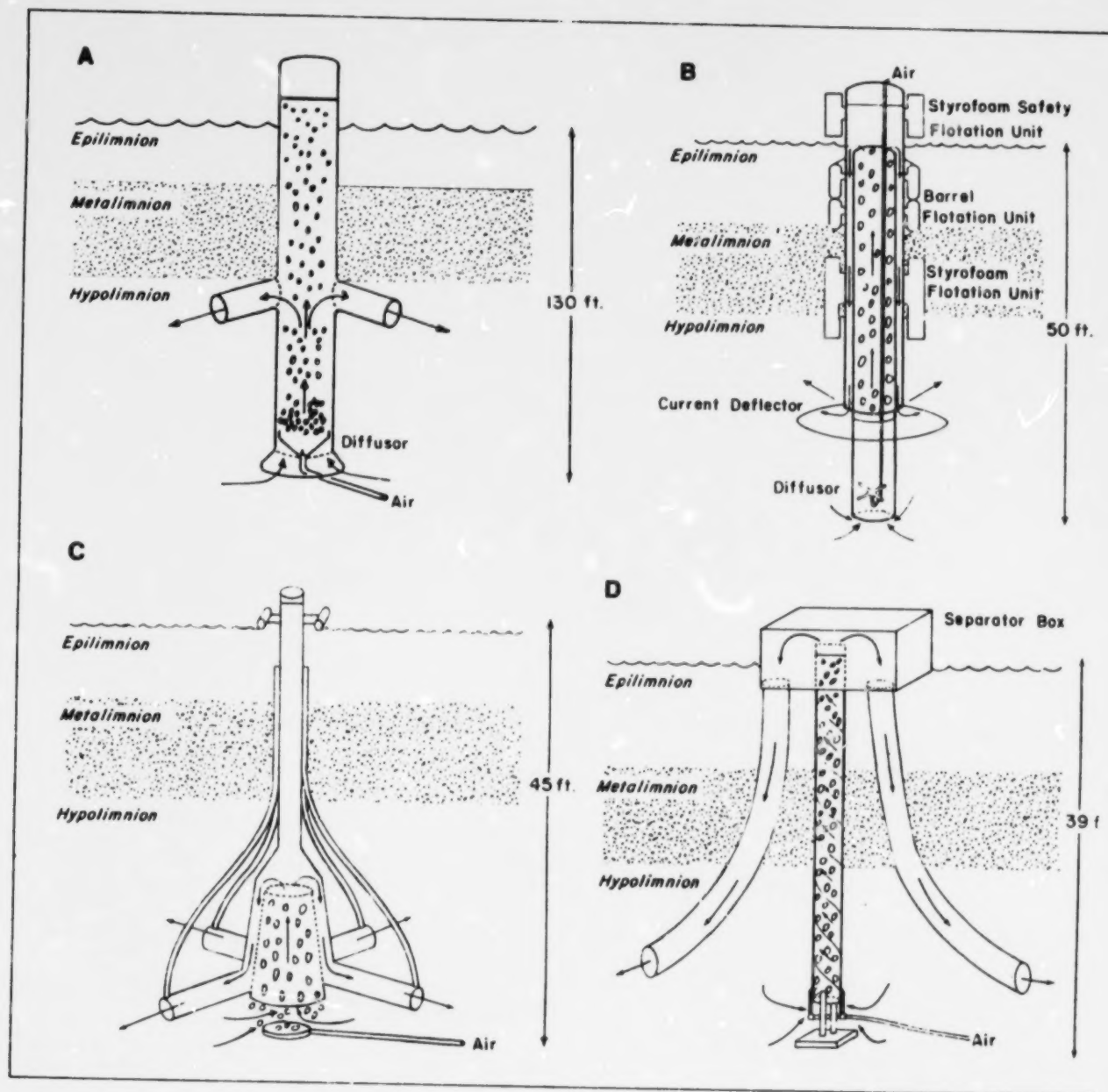


FIGURE 2: Hypolimnetic aeration units: (a) Bernhardt, 1967; (b) Fast, 1971; (c) Union Carbide, 1973; (d) Smith et al., 1975.

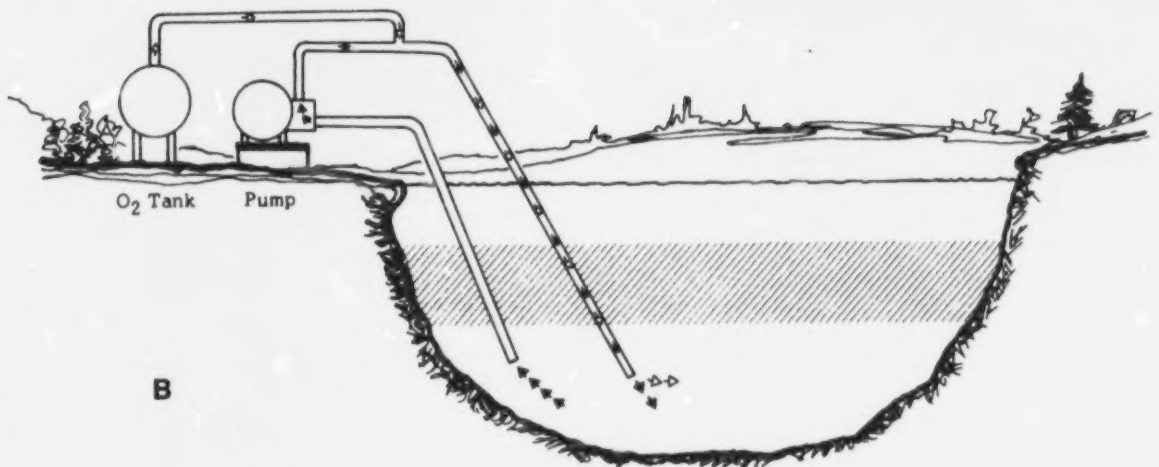
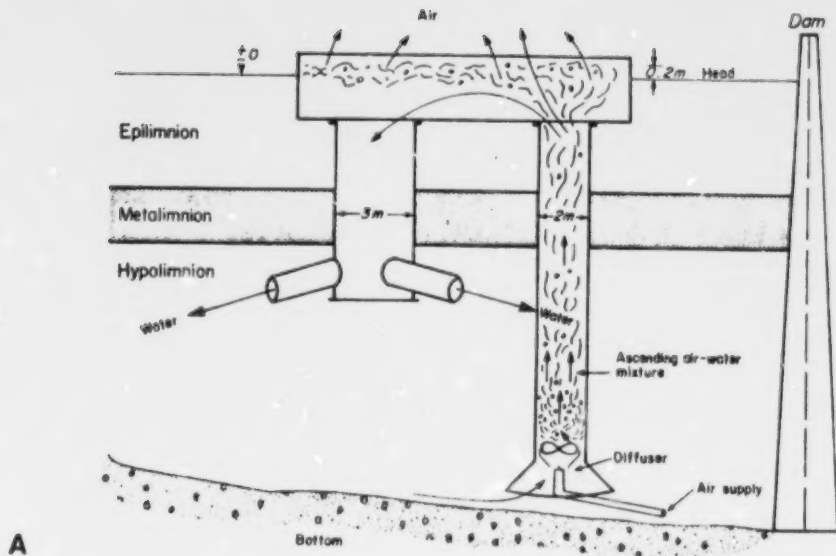


FIGURE 3: Hypolimnetic aeration units: (a) Bernhardt 1967, (in Fast and Lorenzen, 1976); (b) Fast et al., 1975.

3. CONCLUSIONS

Aeration systems have been used to improve water quality of lakes and reservoirs. However in some cases no net benefit and even worsening of conditions have occurred because of inappropriate use of aeration systems. Because of this, a detailed evaluation of prevailing chemical and biological limnology and anticipated effects, as well as an engineering evaluation of most appropriate technology (particularly the size of the components used) is absolutely necessary. A careful scrutiny of the literature is an essential prerequisite prior to undertaking an aeration project.

Commercially manufactured systems are available from a number of companies: destratification systems from Hinde Engineering¹ ("Air Aqua"); hypolimnetic aerators from Atlas-Copco² and Union Carbide³; and wind powered destratification aerators for small lakes (Rieder, 1977) from Lake-Aid⁴.

1* Hinde Engineering, 654 Deerfield Road, P.O. Box 188, Highland Park, Illinois, 60035/Hinde Manufacturing, 260 Burlington Street East, Hamilton Ont., L8L 4H4

2* Atlas Copco AB, S-105, 23 Stockholm Sweden/Atlas Copco, P.O. Box 745, Point Claire, Quebec, H9R AS8

3* Union Carbide Corp., Tarrytown, N.Y.

4* Lake Aid, Route 2, Bismarck, North Dakota, 58501

* No endorsement is implied, only a listing of possible suppliers.

REFERENCES ON DESTRATIFICATION

- Anonymous. 1981. Aeration of sewage lagoons, reservoirs and streams. 1970 - 1981. National Technical Information Service, PB81-807802. 274 p.
- Alavian, V. 1973. Design and construction of a research station for the study of induced vertical mixing in a thermally stratified pond using warm water discharge. NTIS Report No. PB-237 701.
- Ambuhl, H. 1967. Impoundment destratification by mechanical pumping - discussion. Am. Soc. Civ. Eng., Sani. Eng. Div. 83(SA4):141-143.
- Arnold, D.F. 1970. Lake Erie alive but changing. *Conservationist* 25:23.
- Babcock, W.H. 1972. Aeration studies. Colorado Fish. Res. Rev. No. 7. p 17-18.
- Barker, J.L. 1976. Effects of air injection at Prompton Lake, Wayne County, Pennsylvania. *Journal of Research of the U.S. Geological Survey* 4(1):19-125.
- Barnes, M.D. and B.L. Griswold. 1975. Effects of artificial nutrient circulation on lake productivity and fish growth. Spec. Conf. Lake Reaeration Res., Am. Soc. Civ. Eng., Gatlinburg, Tenn.
- Barnett, R.H. 1971. Reservoir destratification improves water quality. *Public Works* 102:60-65.
- Barnett, R.H. 1975. Case study of reaeration of Casitas Reservoir. Spec. Conf. Lake Reaeration Res., Am. Soc. Civil Eng., Gatlinburg, Tenn.
- Bella, D.A. 1970. Simulating the effects of sinking and vertical mixing on algal population dynamics. *J. Wat. Poll. Contr. Fed.* 42(5) pt. 2: R140-R152.
- Bengtsson, L. and C. Gelin. 1975. Artificial aeration and suction dredging methods for controlling water quality. In: *Proceedings of a Symposium, The Effects of Storage on Water Quality*, Reading University, March 1975, Paper 12.
- Bengtsson, L., S. Fleischer, G. Lindmark and W. Ripl. 1975. The Lake Trummen Restoration Project. *Verh. Int. Ver. Limnol.* 19: 1080-1087.
- Bernhardt, H. 1969. Impoundment destratification by mechanical pumping. In Symons, 1969. *Water Quality Behaviour in Reservoirs*. Public Health Service Publication No. 1930, Cincinnati, Ohio. 616 p.
- Bernhardt, H. 1975. Ten years experience of reservoir aeration. *Programs in Water Technology* 7(3/4):483-495.

- Biederman, W.J. and E.E. Fulton. 1971. Destratification using air. Amer. Water Works Assoc. 63(7):462-466.
- Bjork, S. 1971. Restoration of the lakes. Lund University, Limnologiska Institution. Lund, Sweden. 23 p.
- Bjork, S. 1972a. Swedish lake restoration program gets results. Ambio 1(5):153-165.
- Bjork, S. 1972b. Bringing sick lakes back to health. Teknisk Tidskrift, Swed. Assoc. Eng. Arch. 102(11):112-120.
- Bowles, L.G. 1972. A description of the spatial and temporal variations in species composition and distribution of pelagic net zooplankton in the central pool of Eufaula Reservoir, Oklahoma, with comment on forced aeration destratification experimentation. Trans. Kans. Acad. Sci., 75:156.
- Boyter, C.J. and M.P. Wanielista. 1973. Review of lake restoration procedures. Water Resour. Bull. 9(3):499-511.
- Brezonik, P.L., J.J. Delfino and G.F. Lee. 1969. Chemistry of N and Mn in Cox Hollow Lake, Wisconsin, following destratification. Amer. Soc. Civ. Eng., Sani. Eng. Div. 95(SA5):929-940.
- Brown, D.J., T.G. Brydges, W. Ellerington, J.J. Evans, M.F.P. Michalski, G.G. Hitchin, M.D. Palmer and D.M. Veal. 1971. Progress report on the destratification of Buchanan Lake. Ont. Water Res. Comm., AID for Lakes Program (Artificially Induced Destratification).
- Brown, R.J. 1978a. Aeration of sewage lagoons, reservoirs, and streams. NTIS, Springfield, Va. 391-812. NTIS Report NTIS/PS-77/0398.
- Brown, R.J. 1978b. Aeration of sewage lagoons, reservoirs, and streams (citations from the NTIS Data Base). NTIS, Springfield, Va. 391-812.
- Bryan, J.C. 1964. Physical control of water quality. J. Br. Water Works Assoc., Proc. Glasgow Conf. Glasgow, United Kingdom.
- Brynildson, O.M. and S.L. Serns. 1977. Effects of destratification and aeration of a lake on its distribution of planktonic crustacea, yellow perch, and trout. Tech. Bull. 99. Wis. Dep. Nat. Resour. 22 p.
- Burns, J.M. Jr. 1966. Reservoir "turn over" improves water quality. Water and Wastes Eng. 3:81.
- Burton, T.M. 1979. Lake eutrophication problems: Long-term correction solutions. Presented at Michigan State Univ. Inland Lake Eutrophication: Causes, Effects, and Remedies Conf. East Lansing, May 21, 1979. p. 55.

- Busby, M.W. 1973. Air-injection at Lake Cachuma, California. U.S. Geol. Surv., Open-file Rep. Menlo Park, Calif.
- Carr, J.E. and D.F. Martin. 1978. Aeration efficiency as a means of comparing devices for lake restoration. J. Env. Science and Health-Env. Science and Engineering 13(1):73.
- Cassidy, J.J. 1973. Aeration of water with turbine draft tube aspirators. Missouri Water Resources Research Center. Columbia. OWRR-A-044-MO. 23 p.
- Cooley, P. 1970. Wraysbury Reservoir: Prevention of thermal stratification. Second Conf. in Water Qual. and Technol. Budapest, Hungary. 1970.
- Cooley, P., A.R. Steel and J.E. Ridley. 1967. Impoundment destratification by mechanical pumping. Discussion. Amer. Soc. Civ. Eng., Sani. Eng. Div. 93(SA4):139-141.
- David, E.L., R.S. Howe and J. Quigley. Institutional design for water quality management. A case study of the Wisconsin River Basin. Vol. IV. Wisconsin Univ., Madison, Water Resources Center.
- Dick, I. 1977. Developments at international conference on water pollution research (8th), Sydney, Australia, October 17-22, 1976. Delaware Univ., Newark. Dept. of Civil Engineering. / Environmental Protection Agency, Washington, D.C. Office of Air, Land and Water use. EPA/600/9-77-015. 229 p.
- Domrose, R.J. 1963. Aerator evaluation. Mont. Fish and Game Dep., Job Completion Rep., Proj. F-12-R-9, Job III. 11 p.
- Drury, D.D., D.B. Porcella and R.A. Gearheart. 1975. The effects of artificial destratification on the water quality and microbial populations of Hyrum Reservoir. Utah Water Research Lab., Logan. / Office of Water Research and Technology, Washington, D.C. OWRT-A-020-UTAH. 182 p.
- Dunst, R.C., S.M. Born, P.D. Uttomark, S.A. Smith and S.A. Nichols. 1975. Survey of lake rehabilitation techniques and experiences. Wisconsin Dept. of Natural Resources, Madison. / Upper Great Lakes Regional Commission, Washington, D.C. EPA-RB02242. 183 p.
- Eunpu, F.F. 1971. Control of reservoir eutrophication by aeration. Presented at the Amer. Water Works Assoc. Meet. Arlington, Va. 23 p.
- Eunpu, F.F. 1973. Control of reservoir eutrophication. J. Amer. Wat. Works Assoc., 65(4):268-274.
- Eunpu, F.F. 1977. Aeration system controls reservoir eutrophication. Wat. Poll. Contr. 115:21-23.

- Fast, A.W. 1968. Artificial destratification of El Capitan Reservoir by aeration. Part 1. Effects on chemical and physical parameters. Calif. Dep. of Fish and Game, Fish Bull. 141.
- Fast, A.W. 1971a. The effects of artificial aeration on lake ecology. Environ. Prot. Agency, Water Pollut. Control Res. Ser. 16010 EXE 12/71. 470 p.
- Fast, A.W. 1971b. Effects of artificial destratification on zooplankton depth distribution. Trans. Amer. Fish. Soc. 100(2):355-358.
- Fast, A.W. 1973a. Reservoir destratification effects. Water Resources Research, 9(3):607-623.
- Fast, A.W. 1973b. Summertime artificial aeration increases winter oxygen levels in a Michigan Lake. Prog. Fish-Cult. 35(2):82-84.
- Fast, A.W. 1975. Artificial aeration and oxygenation of lakes as a restoration technique. Presented at the March 24-26, 1975 symposium; Recovery of Damaged Ecosystems, Virginia Polytechnic Institute and State University. Blacksburg.
- Fast, A.W. 1979. Artificial aeration as a lake restoration technique. In: Lake Restoration, Report No. EPA 440/5-79-001, p. 121-131.
- Fast, A.W. and J.A. St. Amant. 1971. Nighttime artificial aeration of Puddingstone Reservoir, Los Angeles County, California. Calif. Fish and Game 57(3):213-216.
- Fast, A.W., B. Moss and R.G. Wetzel. 1973. Effects of artificial aeration on the chemistry and algae of two Michigan Lakes. Water Resources Research 8(3):624-647.
- Feliciano, D.V. 1979. EPA's clean lakes program: A return for the money. J. Wat. Poll. Cont. Fed. 51(2):227-232.
- Ferraris, C.J. 1972. Distribution of benthic macroinvertebrates in an artificially destratified reservoir. Master's thesis. Oklahoma State University, Stillwater. Dept. of Zoology. / Office of Water Research and Technology, Washington, D.C. OWRT-A-059-OKLA.
- Fitzgerald, G.P. 1970. Aerobic Lake muds for the removal of phosphorus from lake waters. Limnol. and Oceanogr. 15(4):550-555.
- Fletcher, D.H. 1971. Aeration saves a lake. Parks and Recreation 6(11):23.
- Flick, W. 1968. Dispersal of aerated water as related to prevention of winter-kill. Prog. Fish-Cult. 30(1):13-18.
- Foree, E.G. and R.L. Barrow. 1970. Algal growth and decomposition: Effects on water quality, Phase II. Nutrient regeneration, composition and

- decomposition of algae in batch culture. Kentucky Water Resources Inst., Lexington.
- Forsberg, B.R. and J. Shapiro. 1980. Predicting algal response to destratification. In: Restoration of Lakes and Inland Waters. EPA Report 440/5-81-010, p. 134-139.
- Garner, F. 1971. Oxygenation. Ecology Today 1(5):14.
- Gartman, P.K. 1974. Artificial aeration and destratification of Ottoville Quarry. PH.D. Thesis. The Ohio State University, Columbus. 93 p.
- Garton, J.E., C.E. Rice, J.M. Steichen and J.E. Quinters. 1974. Low energy mechanical methods of reservoir destratification. Oklahoma Agricultural Experiment Station, Stillwater. / Office of Water Resources Research, Washington, D.C. Report No. OWRR-A-028-OKLA.
- Garton, J.E., R.G. Strecker and R.C. Summerfelt. 1978. Performance of an axial flow pump for lake destratification. In: W.A. Rogers, (ed.) Proc. 13th Annu. Conf. S.E. Assoc. Fish Wildl. Agencies. p. 336-346.
- Garton, J.E., R. Summerfelt, D. Toetz, J. Wilhm and H. Jarrell. 1976. Physiochemical and biological conditions in two Oklahoma reservoirs undergoing artificial destratification. Oklahoma State University, Stillwater. Dept. of Agricultural Engineering. Bureau of Reclamation, Denver, Colo. / Office of Water Research and Technology, Washington, D.C. Report No. OWRT-C-5228(4215), OWRT-A-028-OKLA.
- Gebhart, G.E. and R.C. Summerfelt. 1976. Effects of destratification on depth distribution of fish. Am. Soc. Civ. Eng., Jour. Environ. Eng. Div. 102:1215.
- Gebhart, G.E. and M.D. Clady. 1977. Effects of mechanical mixing in reservoirs on seasonal and annual growth rates of fishes. Oklahoma State University, Stillwater. School of Biological Sciences. Oklahoma Water Resources Research Institute, Final Technical Completion Report, December 1977. 42 p. OWRT-A-069-OKLA(1).
- Haffner, G.D. 1977. Spatial distribution of seston in an artificially mixed system. Hydrobiologia 54(3):225-231.
- Haines, B. 1972. Destratification of lakes. Job Progress Report, Federal Aid Project F-22-R-12. N.M. Dep. of Game and Fish.
- Halsey, T.G. 1968. Autumnal and over-winter limnology of three small eutrophic lakes with particular reference to experimental circulation and trout mortality. J. Fish. Res. Bd. Can. 25(1):81-99.
- Halsey, T.G. and D.M. Galbraith. 1971. Evaluation of two artificial circulation systems used to prevent trout winterkill in small lakes. B.C. Fish and Wildl. Br., Fish Manage. Publ. 16.

- Hanson, W.A. and F. Bigelow. 1977. Lake management case study: Westlake Village, California. Urban Land Inst. Technical B. 73, 1977.
- Haynes, R.C. 1973. Some ecological effects of artificial circulation on a small eutrophic lake, with particular emphasis on phytoplankton. Kezar Lake experiment, 1968. *Hydrobiologia* 43(3-4):463-504.
- Haynes, R.C. 1975. Some ecological effects of artificial circulation on a small eutrophic New Hampshire Lake. *Hydrobiologia* 46(1):141.
- Hedman, E. and S. Tyley. 1967. Elimination of stratification at Lake Cachuma, California. United States Geol. Surv. Water Resource Div. Menlo Park, Calif. 40 p.
- Hickel, B. 1978. Phytoplankton succession in the Grebner See during artificial aeration in the hypolimnion. *Arch. Hydrobiol.* 82(1-4):216-230.
- Hogan, W.T., F.E. Reed and A.W. Starbird. 1970. Optimum Mechanical Aeration Systems for Rivers and Ponds. Littleton Research and Engineering Corp., Mass., (203 920). / Environmental Protection Agency, Washington, D.C. EPA-WQO-16080-000-07/70 or EP2.10:16080/D007/70.
- Hooper, F.F., R.C. Ball and H.A. Tanner. 1952. An experiment in the artificial circulation of a small Michigan lake. *Trans. Amer. Fish. Soc.* 82:222-241.
- Horak, G.C. and J.E. Olson. 1972. Wildlife habitat improvement: Some options. *Water Spectrum* 7(3):10.
- Horne, A.J. 1972. Control of blue-green nuisance blooms - the effects of nitrogen fixation, aeration/mixing and related parameters. Clear Lake Algal Res. Unit, 2nd Ann. Report Lakeport, Calif.
- Howard, R.G. 1972. Reservoir destratification improves water quality. *Reclamation Era* 58(1):6.
- Hunter, J.S. 1977. A Basis for Aeration Design. Colorado State University, Fort Collins, Dept. of Civil Engineering. Ph.D Thesis. / Office of Water Research and Technology, Washington, D.C. OWRT-A-008-Colo. / NTIS Report No. PB-290-718.
- Ingols, R.S. 1976. The cause of trout fish kills occurring in the water from the aerated hypolimnion of deep lakes. Georgia Inst. of Tech., Atlanta. Environmental Resources Center. / Office of Water Research and Technology, Washington, D.C. OWRT-A-056-GA(1).
- Inland Fisheries Branch. 1970. Effects of artificial destratification on distribution of bottom organisms in El Capitan Reservoir. Calif. Dep. of Fish and Game, Fish. Bull. 148.

- Irwin, W.H., J.M. Symons and G.G. Robeck. 1966. Impoundment destratification by mechanical pumping. *Am. Soc. Civ. Eng., J. Sanit. Eng. Div.*, 92(SA6):21-40.
- Irwin, W.H., J.M. Symons and G.G. Robeck. 1967. Water quality in impoundments and modifications from destratification. In: Symons, J.M. (ed). *Water Quality Behaviour in Reservoirs*. Public Health Serv. Publ. No. 1930. Cincinnati, Ohio.
- Johnson, R.C. 1966. The effect of artificial circulation on production of a thermally stratified lake. *Wash. Dep. Fish. Res. Pap.* 2(4):5-15.
- Keto, J. and P. Sepanen. 1973. Lake Tuusula destratification and aeration test; winter 1972/73. *Aqua Fennica*, p. 126-136.
- Keup, L.E. 1979. Fisheries in lake restoration. EPA Office of Water & Waste Management, *Fisheries* 4(1):7.
- King, D.L. 1970. Reaeration of Streams and Reservoirs: Analysis and Bibliography. Bureau of Reclamation, Denver, Colo. Engineering and Research Center. REC-OCE-70-55. 140 p.
- Koberg, G.E. 1964. Elimination of thermal stratification in Lake Wohford. Calif. *Calif. U.S. Geol. Surv., Prof. Pap.* 501-D.
- Koberg, G.E. and M.E. Ford. 1965. Elimination of thermal stratification in reservoirs and the resulting benefits. *U.S. Geol. Surv., Water-Supply Pap.* 1809-M.
- Kothandaraman, V., D. Roseboom and R.L. Evans. 1979. Pilot lake restoration investigations: Aeration and destratification in Lake Catherine. Illinois State Water Survey, Urbana. / Illinois Inst. of Natural Resources, Chicago. 58 p.
- Knapp, G.L. 1973. Aeration of Natural Waters: A Bibliography. Office of Water Resources Research, Washington, D.C. Water Resources Scientific Information Center. W73-13651. 363 p.
- Knoppert, P.L., J.J. Rook, T. Hofker and G. Oskam. 1970. Destratification experiments at Rotterdam. *Amer. Water Works Assoc.* 62:448-454.
- Kranenburg, C. 1979. Destratification of lakes using bubble columns. *Am. Soc. Civ. Eng., Hydraul. Div.* 105(H44):333-349.
- Kreil, A. 1969. Air aqua system research in Rolette County. N.D. State Game and Fish Dep., Proj. F-2-R-15, Job 8, Rep. A-1009.
- Kreil, A. 1971. Air aqua system research in Rolette County. N.D. State Game and Fish Dept., Proj. F-2-R-17, Job 8, Rep. A-1015.

- Lackey, R.T. 1971. Effects of artificial destratification of a lake ecosystem. Colo. Div. Game, Fish and Parks. Dingell-Johnson Rep. No. 2. 71 pp.
- Lackey, R.T. 1972a. A technique for eliminating thermal stratification in lakes. *Water Res. Bull.* 8(1):46-49.
- Lackey, R.T. 1972b. Response of physical and chemical parameters to eliminating thermal stratification in a reservoir. *Water Res. Bull.*, 8(3):589-599.
- Lackey, R.T. 1973a. Bottom fauna changes during reservoir destratification. *Water Research* 7(9):1349-1356.
- Lackey, R.T. 1973b. Effects of artificial destratification on zooplankton in Parvin Lake, Colorado. *Trans. Amer. Fish. Soc.* 102:450-452.
- Lackey, R.T. 1973c. Artificial reservoir destratification effects on phytoplankton. *J. Water Pollut. Control Fed.* 45(4):668-673.
- Lackey, R.T. and D.W. Holmes. 1972. Evaluation of two methods of aeration to prevent winterkill. *Prog. Fish-Cult.* 34(3):175-178.
- Laverty, G.L. and H.L. Nielsen. 1970. Quality improvements by reservoir aeration. *Amer. Water Works Assoc.* 62(11):711-714.
- Leach, L.E. 1968. Eufaula Reservoir Aeration Research. Robert S. Kerr Water Research Center, Ada, Okla. 13 p.
- Leach, L.E. and C.C. Harlin Jr. 1970. Induced aeration of small mountain lakes. Robert S. Kerr Water Research Center, Ada, Okla. EPA-WQO-16080-11/70. 58 p.
- Leach, L.E., W.R. Duffer and C.C. Harlin Jr. 1968. Pilot study of dynamics of reservoir destratification. Robert S. Kerr Water Research Center, Ada, Okla. FWPCA-16080-00/68. 37 p.
- Lehmann, E.J. 1973. Aeration systems and processes. A bibliography with abstracts. N.T.I.S., Springfield, Va. 109 p.
- Lehmann, E.J. 1975. Aeration of sewage lagoons, reservoirs, and streams (A bibliography with abstracts). N.T.I.S., Springfield, Va. (391 812). NTIS/PS-75/357/4ST. 164 p.
- Lehmann, E.J. 1976a. Aeration of sewage lagoons, reservoirs, and streams (Citations from the N.T.I.S. data base). N.T.I.S., Springfield, Va. (391 212). 182 p.
- Lehmann, E.J. 1976b. Aeration of sewage lagoons, reservoirs, and streams (Citations from the Engineering Index Data Base). N.T.I.S., Springfield, Va. (391 812). 108 p.

- Lorenzen, M.W. 1977a. Aeration/circulation: keeps algal blooms in check. Part 1. Wastewater Treatment. Water and Wastes Engineering 14(10):69-74.
- Lorenzen, M.W. 1977b. Aeration/circulation: keeps algal blooms in check, Part 2. Wastewater Treatment. Water and Wastes Engineering 14(11):88-92.
- Lorenzen, M.W. and A.W. Fast. 1977. A guide to aeration/circulation techniques for lake management. Tetra Tech. Inc., Lafayette, Calif. / Corvallis Environmental Research Lab., Oreg. EPA/600/3-77/004.
- Lorenzen, M.W. and R. Mitchell. 1973. Theoretical effects of artificial destratification on algal production in impoundments. Environ. Science and Tech. 7(10):939-944.
- Lorenzen, M.W. and R. Mitchell. 1975. An evaluation of artificial destratification for control of algal blooms. Jour. Am. Water Works Assoc. 67:373-376.
- Lung, W. and R.P. Canale. 1977. Projections of phosphorus levels in White Lake. Am. Soc. Civ. Eng., J. Env. Engineering Div. 103(4):663-676.
- MacBeth, S.E. 1973. Some observations on changes in water chemistry and algal growth in artificial destratified lakes in Ontario. Presented at the 36th Ann. Meet. of the Amer. Soc. of Limnol. and Oceanogr. Salt Lake City, Utah.
- McClintock, N. 1976. Effects of artificial destratification on zooplankton of two Oklahoma reservoirs. M.Sc. thesis. Oklahoma State University.
- McCullough, J.R. 1974. Aeration revitalizes reservoir. Water and Sewage Works 121(6):84-85.
- McLaughlin, D.K. and M.R. Givens. 1978. A hydraulic model study of propeller-type lake destratification pumps. Oklahoma State University, Stillwater. School of Mechanical and Aerospace Engineering. / Office of Water Research and Technology, Washington, D.C. Report No. OWRT-A-075-OKLA.
- McNall, W.J. 1971. Destratification of lakes. Job Progress Report, Project F-22-R-11. N.M. Dep. of Game and Fish. 31 p.
- Madrid, M., K. Needham and R.E. Spreece. 1971. Downflow bubble contact aeration. Am. Soc. Civ. Eng., J. Sanitary. Eng. Div. 97(4):433-441.
- Malueg, K., J. Tilstra, D. Schults and C.F. Powers. 1971. The effects of induced aeration upon stratification and eutrophication processes in an Oregon farm pond. Int. Symp. Manmade Lakes, Knoxville, Tenn. May 3-7, 1971.

- Maugh, T.H. 1979. Restoring damaged lakes. *Science* 203(4):425.
- Mercier, P. 1965. Aeration partielle sous-lacustrine d'un lac eutrope (In French). *Verh. Int. Ver. Limnol.* 10:294-297.
- Mercier, P. and S. Gay. 1954. Effets de l'aeration artificielle sous-lacustre au lac de Bret. (In French). *Schweiz Z. Hydrol.* 16:248-308.
- Mercier, P. and J. Perret. 1949. Aeration of Lake Bret. *Monatsbull. Schweiz. Ver. Gas. u. Wasserfachm* 29:25.
- Merna, J.W. 1965. Aeration of winterkill lakes. *Prog. Fish-Cult.* 27(4):199-202.
- Mukerjee, A. 1973. Mass transfer in heterogeneous systems and velocity and gas absorption studies for single bubbles. Iowa State Univ., Ames. Dept. of Chemical Engineering. OWRR-B-030-IA (1). 289 p.
- Murphy, G.I. 1962. Effects of mixing depth and turbidity on the productivity of fish and wildlife. *Trans. Am. Fish Soc.* 91:69-76.
- Neilson, B.J. 1974. Reaeration dynamics of reservoir destratification. *J. Amer. Wat. Works Assoc.* 66(10):617.
- New Hampshire Water Supply and Pollution Control Commission. 1970. Algae control by mixing. Staff Report on Kezar Lake in Sutton, N.H. New Hampshire Water Supply and Pollution Control Commission, Concord, N.H. 109 p.
- Oskam, K. 1971. A kinetic model of phytoplankton growth, and its use in algal control by reservoir mixing. Paper presented at Int. Symp. Manmade Lakes, Knoxville, Tenn. May 3-7, 1971.
- Pastorok, R.A., T.C. Ginn and M.W. Lorenzen. 1980. Evaluation of aeration/circulation as a lake restoration technique. In: *Restoration of Lakes and Inland Waters*. U.S. Environ. Prot. Agency. EPA 440/5-81-010. pp. 124-133.
- Patriarche, M.H. 1961. Air induced winter circulation of two shallow Michigan Lakes. *J. Wild. Manag.* 25(3):282-289.
- Patriarche, M.H. 1963. A test of a commercial device to prevent winter oxygen depletion in a Michigan Lake. *Mich. Inst. for Fish. Res., Rep. No. 1877*. Mich. Dept. of Conserv.
- Puffett, A.J. 1974. Lake restoration by compressed air. *Ecologist* 4(6):233.
- Rapoza, D. 1971. Reservoir aeration improves water quality. *Public Works* 102(5):86-87.

- Rasmussen, D.H. 1960. Preventing winterkill by use of a compressed air-system. *Prog. Fish-Cult.* 22(4):185-187.
- Riddick, T.M. 1957. Forced circulation of reservoir waters yields multiple benefits at Ossining. New York. Water Sewage Works, 104:231.
- Ridley, J.E. 1970. The biology and management of eutrophic reservoirs. *Proc. Soc. Water Treat. Exam.* 19:374-399.
- Ridley, J.E. 1972. New approaches to water quality control in impoundments. In: Mitchell R. (ed.), *Water Pollution Microbiol.* New York, N.Y.
- Ridley, J.E., P. Cooley and J.A.P. Steel. 1966. Control of thermal stratification in Thames Valley reservoirs. *Proc. Soc. Water Treatment and Exam.* 15:225-244.
- Rieder, W.G. 1977. Wind powered artificial aeration of northern prairie lakes. North Dakota Water Resources Research Inst., Fargo. / North Dakota State Univ., Fargo. Dept. of Mechanical Engineering. // Office of Water Research and Technology. Washington, D.C. OWRT-B-040-NDAK (1). 121 p.
- Robinson, E.L., W.H. Irwin and J.M. Symons. 1969. Influence of artificial destratification on plankton population in impoundments. In: J.M. Symons (ed.), *Water Quality Behavior in Reservoirs*. Publ. Health Serv. Publ. No. 1930. Cincinnati, Ohio.
- R.S. Kerr Research Center. 1970. Induced aeration of small mountain lakes. *Water Pollut. Control Res. Ser.* 16080-11/70. U.S. Environ. Prot. Agency.
- Schierholz, P.M., W.L. Somerwell, W. Babcock, R. Hartel and K. Timbre. 1976. Wind-powered aeration for remote locations. Colorado Div. of Wildlife, Fort Collins. / Colorado State Univ., Fort Collins. // Energy Research and Development Administration. 152 p.
- Schmitz, W.R. and A.D. Hasler. 1958. Artificially induced circulation of lakes by means of compressed air. *Science* 128:1088-1089.
- Scott, W. and A.L. Foley. 1919. A method of direct aeration of stored waters. *Proc. Ind. Acad. Sci.*, p. 71-73.
- Seaburg, K.G. 1966. Aerator evaluation. Mont. Fish and Game Dep., Job Completion Rep., Proj. F-12-R-11, Job III. 12 p.
- Shapiro, J. 1979. The need for more biology in lake restoration. *Proc. Natl. Conf. Lake Restoration*. U.S. Environ. Prot. Agency. EPA 440/5-79-001 pp. 161-168.
- Shapiro, J., V. Lamarra and M. Lynch. 1975. Biomanipulation: An ecosystem approach to lake restoration. In: P.L. Brezonik and J.L. Fox, (eds.) *Proc. Symp. Water Quality Manage. Through Biological Control*.

University of Florida and U.S. Environ. Prot. Agency. Gainesville. pp. 85-95.

- Shapiro, J., G. Zeto and V. Lamarre. 1977. Experimental studies on changing algal populations from blue-greens to greens. Minnesota Univ., Minneapolis. Limnological Research Center. / Aquaculture Research Corp., Dennis, Mass. // Utah State Univ., Logan. Dept. of Wildlife Science. /// Office of Water Research and Technology, Washington, D.C. OWRT-B-087-MINN (1). 30 p.
- Shuler, J. 1972. How a lake aeration system overcame water consumer complaints. Public Work. 103(5):92-93.
- Sikarowa, A. 1977. Changes of the distribution and number of the bottom fauna as an effect of artificial lake aeration. In: Proceedings: 20th Congress, International Vereinigung fur Theoretische und Angewandte Limnologie; Copenhagen, Denmark Vol. 20. September 1978. Part 2:p. 1000-1003.
- Smith, S.A., D.R. Knauer and T.L. Wirth. 1975. Aeration as a lake management technique. Wisconsin Dept. of Natural Resources Technical Bull. 87.
- Speece, R.E. 1969. The use of pure O₂ in river and impoundment aeration. Presented at the 24th Ind. Waste Conf. Purdue, Indiana.
- Steichen, J.M. 1974. The effect of lake destratification on water quality parameters. Unpubl. thesis, Oklahoma State University. Stillwater, Oklahoma.
- Steichen, J.M., J.E. Garton and C.E. Rice. 1979. The effect of lake destratification on water quality. Amer. Water Works Assoc. April 1979: p. 219-225.
- Strecker, R.J., J.M. Steichen, J.E. Garton and C.E. Rice. 1977. Improving lake water quality by destratification. Trans. Am. Soc. Agric. Eng. 20:4-713.
- Summerfelt, R.C. and G. Gebhart. 1976. Fish growth response to mechanical mixing of Lake Arbuckle, Oklahoma. Oklahoma Cooperative Fishery Research Unit, Stillwater. / Office of Water Research and Technology, Washington, D.C. // Oklahoma Water Resources Research Inst., Stillwater. OWRT A-048-OKLA (1). 110 p.
- Symons, J.M. 1969. Water Quality Behaviour in Reservoirs. A Compilation of Published Research Papers. Bureau of Water Hygiene, Cincinnati, Ohio. 618 p.
- Symons, J.M. 1971. Artificial destratification in reservoirs. Jour. Am. Water Works Assoc. 63(9):597-604.
- Symons, J.M., J.K. Carswell and G.G. Robeck. 1970. Mixing of water supply reservoirs for quality control. Jour. Am. Water Works Assoc. 62:322.

- Symons, J.M., W.H. Irwin and G.G. Robeck. 1967. Reservoir water quality control by destratification. Fed. Water Pollut. Control Adm., Cincinnati, Ohio.
- Symons, J.M., W.H. Irwin, E.L. Robinson and G.G. Robeck. 1967. Impoundment destratification for raw water quality control using either mechanical or diffused air pumping. Amer. Water Works Assoc. 59(10):1268-1291.
- Toetz, D.W. 1977a. Biological and water quality effects of whole lake mixing. Oklahoma State Univ., Stillwater. School of Biological Sciences. / Oklahoma Water Resources Research Inst., Stillwater. // Office of Water Research and Technology, Washington, D.C. OWRT-A-068-OKLA (1). 87 p.
- Toetz, D.W. 1977b. Effects of lake mixing with an axial flow pump on water chemistry and phytoplankton. *Hydrobiologia* 55:129.
- Toetz, D.W. 1979. Biological and water quality effects of artificial mixing of Arbuckle Lake, Oklahoma, during 1977. *Hydrobiologia* 63:255.
- Toetz, D.W. 1981. Effects of whole lake mixing on water quality and phytoplankton. *Water Research* 15:1205-1210.
- Toetz, D., J. Wilhm and R. Summerfelt. 1972. Biological Effects of Artificial Destratification and Aeration in Lakes and Reservoirs - Analysis and Bibliography. U.S. Dep. Inter. Bur. of Reclam. Rep. No. 12-D-2121 and -2122 (REC-ERC-72-33). Denver, Colo. 117 p.
- Torrest, R.S. and J. Wen. 1976. Mixing and circulation of lakes and reservoirs with air plumes. New Hampshire Univ., Durham. Water Resources Research Center. / New Hampshire Univ., Durham. Dept. of Chemical Engineering. // Office of Water Research and Technology, Washington, D.C. OWRT-A-030-NH (2). 135 p.
- Tubb, R. 1966. Limnological conditions in aerated lakes of the Turtle Mountains. N.D. Game and Fish Dep., Proj. F-2-R-13, Job 19, Rep. A-1001.
- Van Ray, L.C. 1968. Evaluation of artificial aeration in Stockade Lake. S.D. Dep. of Game, Fish and Parks, Proj. F-15-R-3, Job 1.
- Vick, H.C., D.W. Hill, H.A. True, R.J. Bruner and T.O. Barnwell. 1977. Preimpoundment Study, Little Black Creek Drainage Basin, Black Creek Watershed, Bulloch County, Georgia. Environmental Protection Agency, Athens, Ga. Surveillance and Analysis Div. / Soil Conservation Service, Athens, Ga. EPA/904/9-77-026.
- Weiss, C.M. and B.W. Breedlove. 1973. Water Quality Changes in an Impoundment as a Consequence of Artificial Destratification. North Carolina Water Resources Research Inst., Raleigh. OWRR-B-077-NC (6). 236 p.
- Wen, C.J. 1974. An experimental study of flow and oxygen transfer in circulation induced by air bubble plumes. NTIS PB-288-388. 195 p.

- Whalls, M. 1968. Destratification benefits to fisheries management. Presented at the Seminar on Reservoir Destratification. Calif. Dep. of Water Resour., Los Angeles, Calif.
- Wildman, R.B., W.C. Wildman, G.E. Rottinhaus and B.L. Benner. 1975. Improving Water Quality by Control of Algae: Cellular and Extracellular Blue-Green Algal Polysaccharides. Iowa State Water Resources Research Inst., Ames. / Office of Water Research and Technology, Washington, D.C. OWRT-B-043-1A (1). 131 p.
- Wilhm, J. and N. McClintock. 1978. Dissolved oxygen concentration and diversity of benthic macroinvertebrates in an artificially destratified lake. *Hydrobiologia* 57:163.
- Wirth, T.L. 1970. Mixing and aeration systems in Wisconsin Lakes. In: Schneberger, E. (ed). A Symposium on Management of Mid Western Winter Kill Lakes. Amer. Fish Soc., North Central Div. Spec. Publ. p. 31-45.
- Wirth, T.L. and R.C. Dunst. 1967. Limnological changes resulting from artificial destratification and aeration of an impoundment. Wisconsin Conserv. Dep., Fish. Res. Rep. No. 22.
- Wirth, T.L., R.C. Dunst, P.D. Uttormark and W. Hilsenhoff. 1970. Manipulation of Reservoir Waters for Improved Quality and Fish Population Response. Wisconsin Dept. of Natural Resources, Madison. Res. Rep. #62.
- Woods, D.E. 1961. The effects of compressed air on winter oxygen levels in a fertile southern Minnesota lake. Minn. Fish and Game, Invest. Rep. No. 230, Invest. Fish. Ser. No. 3 p. 51-62.
- Wood, M.L. and L.E. Leach. 1969. Current research on reservoir destratification. Tech. Rep. No. 20. Proc. Ann. Environ. and Water Resour. Eng. Conf. 8:71-86. Nashville, Tenn.
- Yount, J.L. and R.A. Crossman Jr. 1966. Causes and Relief of Hyper-Eutrophication of Lakes. Florida State Board of Health, Vero Beach. Entomological Research Center. 67 p.
- Yu, S.L., T.J. Tuffy and D.S. Lee. 1977. Atmospheric Reaeration in a Lake. Rutgers - The State Univ., New Brunswick, N.J. Water Resources Research Inst. / Office of Water Research and Technology, Washington, D.C. OWRT-A-041-NJ (1). 60 p.
- Zieminski, S.A. and R.C. Whittemore. 1970. Induced Air Mixing of Large Bodies of Polluted Water. Maine Univ., Orono. Dept. of Chemical Engineering. EPA-WQO-16080-DWP-11/70. 58 p.

REFERENCES ON HYPOLIMNETIC AERATION

- Ashley, K.I. 1981. Effects of hypolimnetic aeration on functional components of the lake ecosystem. M Sc. Thesis, Dept. Zoology, University of British Columbia.
- Ashley, K.I. in prep. Factors controlling oxygen depletion in B.C. winter kill lakes.
- Barica, J. 1974. Extreme fluctuations in water quality of eutrophic fish kill lakes: effect of sediment mixing. *Water Research* 8:881-888.
- Bengtsson, L. and C. Gelin. 1975. Artificial aeration and section dredging methods for controlling water quality. In: *Proceedings of Symposium, The Effects of Storage on Water Quality*, Reading University, March 1975, Paper 12.
- Bernhardt, H. 1967. Aeration of Wahnback Reservoir without changing the temperature profile. *J. Amer. Water Works Assoc.* 59(8):943-964.
- Bernhardt, H. and G. Hotter. 1967. Möglichkeiten der Verhinderung anaerober Verhältnisse in einer Trinkwassertalsperre während der Sommerstagnation (In Germany). *Arch. Hydrobiol.* 63(6):404-428.
- Bianucci, G. and E.R. Bianucci. 1979. Oxygenation of a polluted lake in northern Italy. *Effluent and Water Treatment Journal* 19(3):117-127.
- Bjork, S. 1972. Swedish lake restoration program gets results. *Ambio* 1(5):153-165.
- Bjork, S. 1972. Bringing sick lakes back to health. *S. Teknisk Tidskrift* 11:3-6.
- Chen, R.L., D.R. Keeney and L.J. Sikora. 1979. Effects of hypolimnetic aeration of nitrogen transformations in simulated lake sediment-water systems. *J. Env. Quality* 8(3):429-433.
- Fast, A.W. 1971. The effects of artificial aeration on lake ecology. *Environ. Prot. Agency, Water Pollution Control Res. Ser.* 16010 EXE 12/71. 470 p.
- Fast, A.W. 1973. Restoration of eutrophic lakes by artificial hypolimnetic oxygenation. In: *Human-Accelerated Eutrophication of Freshwater Lakes. Proceedings of a Conference, December 1973.* Ossining New York. p 21-34.
- Fast, A.W. 1979. Artificial aeration as a lake restoration technique. In: *Lake Restoration, Proceedings of a National Conference, EPA 440/5-79-001*, p. 121-131.

- Fast, A.W., V.A. Dorr and R.J. Rosen. 1975. A submerged hypolimnion aerator. *Water Resources Research* 11(2):287-293.
- Fast, A.W., W.J. Overholtz and R.A. Tubb. 1975. Hypolimnetic oxygenation using liquid oxygen. *Water Resources Research* 11(2):294-299.
- Fast, A.W., W.J. Overholtz and R.A. Tubb. 1977. Hyperoxygen concentrations in the hypolimnion produced by injection of liquid oxygen. *Water Resources Research*. 13(2):474-476.
- Fast, A.W. and M.W. Lorenzen. 1976. Synoptic survey of hypolimnion aeration. *Amer. Soc. civ. Eng., J. Env. Engineering Div.*, 102(6):1161-1173.
- Fast, A.W., M.W. Lorenzen and J.H. Glenn. 1976. Comparative study with costs of hypolimnetic aeration. *Amer. Soc. Civ. Eng., J. Env. Engineering Div.*, 102(6):1175-1187.
- Fitzgerald, G.P. 1970. Aerobic lake muds for the removal of phosphorus from lake water. *Limnol. Oceanogr.* 15:550-555.
- Garrell, M.H., J.C. Confer, D. Kirschner and A.W. Fast. 1977. Effects of hypolimnetic aeration on nitrogen and phosphorus in a eutrophic lake. *Water Resources Research* 13(2):343-347.
- Garrell, M.H., A.M. Gibbs and R.L. Miller. 1978. Maintenance of a trout fishery by aeration in a eutrophic lake. *New York Fish and Game Journal* 25(1):79-82.
- Imboden, D.M. and R. Gachter. 1978. A dynamic lake model for trophic state prediction. *Ecological Modelling* 4(2-3):77-98.
- Jennett, J.C., R.H. Clark and C.M. Pai. 1972. Hypolimnion reaeration of small reservoirs and lakes. Office of Water Resources Research, Washington, D.C. OWRR-A-053-MO.
- Keto, J. and P. Seppanen. 1973. Lake Tuusula destratification and aeration test; winter 1972/73. *Aqua Fennica*, p 126-136.
- Leach, L.E., W.R. Duffer and C.C. Curtis. 1970. Induced hypolimnion aeration for water quality improvement of power releases. Environmental Protection Agency, Robert S. Kerr Water Research Center, Ada, Akla. Report No. EPA-WQO-16080-10/70.
- Lorenzen, M. and A.W. Fast. 1977. A Guide to aeration/circulation techniques for lake management. Environmental Protection Agency, Washington, D.C. Report No. EPA-600/3-77-004, January 1977.
- Mercier, P. and J. Perret. 1949. Aeration of Lake Bret. *Monatsbull. Schweiz. Ver. Gas. u. Wasserfachm.*, 29:25.

- Meyer, O. 1974. Restoration of lakes and other water bodies. Engineering Digest 20(4):37-40.
- Overholtz, W.J., A.W. Fast, R.A. Tubb and R. Miller. 1977. Hypolimnion oxygenation and its effects on the depth distribution of Rainbow Trout (*Salmo gairdneri*) and Gizzard Shad (*Dorosoma cepedianum*). Trans. Amer. Fish Society 106(4):371-375.
- Smith, S.A., D.R. Knauer and T.L. Wirth. 1975. Aeration as a lake management technique. Wisconsin Dept. of Natural Resources Technical Bull. 87.
- Serns, S.L. 1976. Movement of Rainbow Trout across a metalimnion deficient in dissolved oxygen. Prog. Fish-Cult. 38(1):54.
- Speece, R.C. 1971. Hypolimnion aeration. Amer. Water Works Assoc. 63(1)6-9.
- Speece, R.E., F. Rayyan and G. Murfee. 1973a. Hypolimnion aeration with commercial oxygen. Volume I. Dynamics of bubble plume. Environmental Protection Agency Technology Series. Report No. EPA-660/2-73-025a.
- Speece, R.E., F. Rayyan and G. Murfee. 1973b. Hypolimnion aeration with commercial oxygen. Volume II. Bubble plume gas transfer. Environmental Protection Agency, Washington, D.C. EPA Series C2874H3 Report No. EPA/660/2-73-025b.
- Theis, T.L. 1979. Physical and chemical treatment of lake sediments. In Lake Restoration. Environmental protection Agency Report No. EPA 440/5-79-001. p. 115-120.
- Union Carbide. 1973. Hypolimnion aeration/oxygenation. Aquatic Environ. Sci. press kit. Tarrytown, N.Y.
- Whipple, W. 1973. Mobile oxygen dispersion craft. Water Resources Bulletin 9(4): 639-646.
- Wirth, T.L., D.R. Knauer and S.A. Smith. 1975. Total and hypolimnetic aeration of lakes in Wisconsin. Verh. Internat. Verein. Limnol. 19:1960-1970.

LIST OF A.P.D. BULLETINS

A BULLETIN is one of four Regular Publication series produced by the Assessment and Planning Division. (This series replaces the former Resource Analysis Branch series). Bulletins present the results of technical or scientific studies including the interpretation or application of resource data.

- APD BULLETIN 1 - Saanich Peninsula Spring-Time Freeze Risk. R.R.H. Chilton.
- APD BULLETIN 2 - Soil and Vegetation Resources of the Pend-d'Oreille Valley, B.C. T. Vold, R.F. Ferster, T.K. Ovanin, R.D. Marsh, G.P. Woods.
- APD BULLETIN 3 - Regional Hydrology of the Northeast Coal Study Area. Michael J. Miles.
- APD BULLETIN 4 - Studies on Aquatic Macrophytes Part XXXI. J.R. Rudolph, C.E.W. Dyer.
- APD BULLETIN 5 - Terrain Inventory and Geological Hazards: Northern Vancouver Island. D.E. Howes.
- APD BULLETIN 6 - Killer Whales and Coastal Log Management: An Overview of Future Uses of Robson Bight, British Columbia. The Robson Bight Study Team.
- APD BULLETIN 7 - Biophysical Resources of the East Kootenay Area: Terrain. J.M. Ryder.
- APD BULLETIN 8 - Biophysical Resources of the East Kootenay Area: Outdoor Recreation. L.E. (Beth) Collins.
- APD BULLETIN 9 - Oil Tanker Traffic: Assessing the Risks for the Southern Coast of British Columbia. W.H. Wolferstan.
- APD BULLETIN 10 - Resources of the Graystokes - Report to Task Group. Technical Subcommittee.
- APD BULLETIN 11 - Fraser River Estuary Study, Water Quality, Dry Weather Storm Sewer Discharges. M. Clark, P. Krahn, J. Walker.
- APD BULLETIN 12 - Phosphorus Retention of Shawnigan Lake Watershed Soils: Management Implications for Subsurface Disposal Systems. N.K. Nagpal.
- APD BULLETIN 13 - Shawnigan Lake Watershed Study: Background Report 1. Use of Percolation and Hydraulic Conductivity Measurements in Design and Management of Soil Waste Disposal Systems. N.K. Nagpal.
- APD BULLETIN 14 - Shawnigan Lake Watershed Study: Background Report 2. An Evaluation of Use of Ceramic Cup Soil Water Samplers in Nutrient Transport Studies. N.K. Nagpal.
- APD BULLETIN 15 - Eurasian Water Milfoil Studies Volume 1: The Effect of Eurasian Water Milfoil (*MYRIOPHYLLUM SPICATUM* L.) on Fish and Waterfowl in the Okanagan Valley, 1977. M.C. Robinson.
- APD BULLETIN 16 - Kootenay Air and Water Quality Study, Phase II: Water Quality in the Upper Columbia River Basin.
- APD BULLETIN 17 - Studies on Aquatic Macrophytes Part XXXIV - The 1980 Aquatic Plant Quarantine Project. R. Dove and M. Wallis.
- APD BULLETIN 18 - Fraser River Estuary Study, Water Quality, Survey of Dissolved Oxygen in 1978. W.A. Bergerud, L.J. Alexander.
- APD BULLETIN 19 - Vegetation Resources of the Vernon Map Sheet Area. Volumes 1 and 2. C.J. Clement.
- APD BULLETIN 20 - Kootenay Air and Water Quality Study, Phase II: Water Quality in the Kootenay River Basin.
- APD BULLETIN 21 - Fraser River Estuary Study, Water Quality, Survey of Fecal Coliforms in 1978. R.J. Rocchini, W.A. Bergerud, R.W. Drennan.
- APD BULLETIN 22 - A Review of Lake Aeration as a Technique for Water Quality Improvement. R.N. Nordin, C.J.P. McKean.